Acta of Turin Polytechnic University in Tashkent

Volume 10 | Issue 1 Article 1

July 2020

GROWING NICKEL GERMANOSILICIDIUM FILMS ON A SI 1-XGEX SINGLE CRYSTAL AND STUDYING THEIR STRUCTURAL AND SOME PHOTOELECTRIC PROPERTIES

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ACTA TTPU

I. FUNDAMENTAL SCIENCE

GROWING NICKEL GERMANOSILICIDIUM FILMS ON A $SI_{1-X}GE_X$ SINGLE CRYSTAL AND STUDYING THEIR STRUCTURAL AND SOME PHOTOELECTRIC PROPERTIES

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Abstract

Based on the chemical elements of group IV,the charge state and proximity of the covalent radii of the molecules of the solution-forming components, the possibility of the formation of substitutional solid solutions, such as: $Si_{1-x}Ge_x$, $Si_{1-x}Sn_x$, $(Si_2)_{1-x}(SnC)_x$, is predicted , $Ge_{1-x}Sn_x$,$(Ge_2)_{1-x}(SiSn)_x$,$(SiC)_{1-x}(GeC)_x$,$(GeC)_{1-x}(SnC)_x$,$(SiGe)_{1-x}(SnC)_x$. Single-crystal films of the substitutional solid solution $Ni_y(Si_{1-x}Ge_x)_{1-y}$ ($0 \le x \le 0.25$) were grown on substrates of a bulk single-crystal $Si_{1-x}Ge_x$ by solid-state reaction during annealing under a vacuum condition of 10^{-7}-10^{-8}torr. X-ray diffraction patterns, spectral photosensitivity, and current-voltage characteristics of the obtained $p/Si_{1-x}Ge_x$ - n / $Ni_y(Si_{1-x}Ge_x)_{1-y}$ heterostructures were studied. The lattice parameters of the epitaxial film are obtained a_f = 5.4451323 and the substrate a_s = 5. 6561. The spectral photosensitivity of p / $Si_{1-x}Ge_x$ - n / $Ni_y(Si_{1-x}Ge_x)_{1-y}$ 5heterostructures covers a photon energy range from 0.9 to 2.5 eV. It is shown that the direct branch of the current – voltage characteristics of the studied structures at low voltages (up to 0.5 V) is described by the exponential dependence $I = I_0 \exp(qV / ckT)$, and at large (V> 0.5 V) the power dependence $I \propto V^{\alpha}$, **c** values: **α** = 2 for V = (0. 5−0. 9) V, **α** = 1. 3 for V = (0. 9−1. 4) V and **α** = 2 for V> 1.4 V. The experimental results are explained based on the double injection model for the n – p – p structure using the drift mechanism of current transfer in the ohmic relaxation mode, taking into account the inertia of the electron exchange inside the recombination complex.

Keywords: silicon, germanium, nickel germanosilicidium, isovalent impurity, alloy decomposition, optical band gap, conductivity, density of the localized states.

Introduction

Studies of the production technology and the study of the physical properties of two- and multicomponent complex semiconductor materials, based on semiconductor and semi-metallic elements of group IV, have shown the vialibity of these materials. Studies show that with a certain selection of components and alloying impurities, it is possible to control their operational parameters and functionality [1–4]. These studies focused on the optical [5,6], thermodynamic [7,8] properties and structural features [9,10] of the $Ge_{1-x}Si_x$, $Ge_{1-x}Ni_x$, $Si_{1-x}Sn_x$, $Si_{1-x}C_x$, $Si_{1-x-y}Sn_xC_y$. Depending on the component composition, the band gap of such semiconductors varies in a wide range - from ~ 0.3 to ~ 2 eV; therefore, they can be used as active elements of optoelectronic devices operating in the far and near infrared radiation spectrum.

In recent years, the epitaxial layers $A^{IV}_{1-x}B^{IV}_x$ grown on Si substrates are finding more and more effective application in opto-, micro-, and nanoelectronics as accessible substrates. The $Si_{1-x}Ge_x$ solid solution(SS) layers with different x values overlap the lattice parameter from equal Si (a = 5. 4198) to equal Ge (a = 5. 6560); therefore, different semiconductor compounds of class $A^{III}B^{V}$ and $A^{II}B^{IV}$ with minimum misfit dislocation density.

At present, nickel germanosilicides play an important role in the preparation of ohmic contacts for the manufacture of modern microchips and integrated circuits based on $Si_{1-x}Ge_x$ epitaxial layers. Nickel germanosilicides began to attract the attention of scientists due to their low cost, they do not require high-temperature treatments, and are compatible with silicon planar technology. The possibility of synthesis at sufficiently low temperatures in comparison with other silicides. Temperature stability with low resistance.

In this paper, we present the results of experimental studies on the growth by a solid-phase reaction, as well as the structural and some photoelectric properties of $Si_{1-x}Ge_x$

solid solution.

2. Methods of growing substitutional solid solutions

2.1. The conditions for the formation of continuous solid solutions substitutions based on elementary semiconductors A ^{IV} B ^{IV}.

The main point of our consideration is that molecular elements of group IV of the type C_2, Si_2, Ge_2, Sn_2 and combinations of elements of the type SiC, GeC, SnC, SiGe, SiSn, GeSn, which do not appear on the traditional state diagrams as compounds, are considered as new chemical compounds that are involved in the formation of solid solution substitution as system components. To predict possible solid solution based on elements of group IV, we proceed from the thermodynamic principle of crystal chemistry, which consists in the fact that in any physical and chemical system whose components are chemical elements, there is a chemical interaction between atoms or molecules. At low temperatures, the atoms tend to be located relative to each other in such a way as to obtain the largest possible gain in energy for given effective charges and atomic sizes. This arrangement of atoms is hindered by structural capabilities, and thermal motion at high temperatures [13].

If, upon the displacement of two chemical elements or compounds and the formation of their solid solution, the energy of elastic distortions of the crystal lattice of the solvent due to the dissolution of the foreign element (occurrence of its atom) is sufficiently small, then the change in the enthalpy $\Delta H_{displ} \ll T\,\Delta S_{displ}$ and the change in the thermodynamic potential Z of the system,

$$\Delta Z_{displ} = \Delta H_{displ} - T\,\Delta S_{displ} < 0, \qquad (1)$$

where H_{displ} is the mixing enthalpy, S_{displ} -is the mixing entropy, T- is the absolute temperature. Therefore, there are numerous cases when, under favorable thermodynamic conditions, solid solution substitutions are formed in accordance with the growth of ΔS_{displ}.

The temperature of the formation of molecules (reaction) Tr, below which epitaxial layers of solid solution should be grown, is limited by the fact that the binding energy Eb between the atoms of the molecules of the compound

$$E_b > \frac{\gamma}{N} \approx kT_r, \qquad (2)$$

where N is the number of atoms of the solid solution, γ is the energy of its thermal vibrations at Tr, k is the Boltzmann constant. Minimum Growth Temperature Solid Solution it is limited by the diffusion rate of atoms and molecules on the surface of a growing crystal (phase boundary), which ensures the formation of a surface (two-dimensional) solid solution.

When cooled to epitaxy temperatures $T \le T_r$, molecules A_2 and BC are formed in the initial phase (A, B, C are chemical elements). If the concentration $N_{BC} \gg N_{A2}$ and the initial phase is saturated with the component BC, then the epitaxial layer solid solution $(BC)_{1-x}(A2)_x$ is deposited, and if $N_{A2} \gg N_{BC}$, then the saturation A_2 - $(A_2)_{1-x}(BC)_x$. On the other hand, in accordance with the statistical law of energy distribution of particles of systems in the initial phase, the formation and decay of molecules A_2 and BC, the concentration of whichN_{A2}, $N_{BC} \ll N_A$, N_B, N_C. If the lifetime of the A_2 or B_C molecules is longer than the time of their transition from the crystallization front to the epitaxial layer, then$(BC)_{1-x}(A_2)_x$ or $(A_2)_{1-x}(BC)_x$, depending on the ratio of the concentrations of N_{A2} and N_{BC}. At the epitaxy temperature, the diffusion of components in the solid phase should not occur.

Under certain thermodynamic conditions, the possibility of the formation of SSs for the substitution of chemical elements is determined by the type of crystal lattices forming a solution of the components, their charge states, and geometric dimensions. Considering these factors and the possibility of substituting the two, three, or four nearest neighboring atoms of the solvent m, respectively, with two-, three-, or four-atomic molecules of the soluble compound n, the conditions for the formation of SS substitutions in the following form were proposed in [14, 15]:

$$\Delta z = \sum_{i=1} z_i^m = \sum_{i=1} z_i^n = 0, \qquad (3)$$

$$\Delta r = \left| \sum_{i=1} r_i^m - \sum_{i=1} r_i^n \right| \le 0.1 \sum_{i=1} r_i^m, \qquad (4)$$

On (4) the equation $Z_i^m Z_i^m$ and where $Z_i^n Z_i^n$ are valences; $r_i^m r_i^m$ and $r_i^n r_i^n$-are the covalent radii of the atoms of solvent m and soluble n chemical element or elements forming molecules of solvent m and soluble n compounds, respectively, i = 1, 2, 3, 4. Condition (3) provides for the electroneutrality of the soluble chemical elements or compounds in a solvent semiconductor material. It is performed when soluble

the elements are isovalent with respect to the solvent semiconductor. Condition (4) provides for the proximity of the geometric parameters of solvent m and soluble n compounds, eliminating the occurrence of significant distortions of the crystal lattice in solid solutions. The smaller 1r, the lower the energy of elastic distortions of the crystal lattice; therefore, the greater the crystal perfection of SS and the greater the solubility of n in m. When the difference in the sum of the covalent radii of the atoms of the molecules of the solution-forming components is more than 10%, the formation of SS of these components is insignificant.

$$\Delta z = (z_A + z_A) - (z_B + z_C) = 0, \qquad (5)$$

$$\Delta r = \left|(r_A + r_A) - (r_B + r_C)\right| \le 0.1(r_A + r_A),$$

$$\Delta r = \left|(r_A + r_A) - (r_B + r_C)\right| \le 0.1(r_B + r_C), \qquad (6)$$

Case i = 1 expresses the condition for the formation of TP substitution of atoms of chemical elements A, B,…solvent atoms of the elements C, D,. . . a soluble element or compound according to the formula $A_{1-x}C_x$ or $AB_{1-x}D_x$, for example, $Si_{1-x}Ge_x$, $GaAs_{1-x}Sb_x$.

If i = 2, then (3) and (4) express the conditions for the formation of the solid solution substitution of two adjacent solvent atoms by a diatomic soluble semiconductor molecule according to the formula $(AB)_{1-x}(CD)_x$ or $(A2)_{1-x}(CD)_x$, e.g., $(GaAs)_{1-x}InP)_x$, $(GaAs)_{1-x}(ZnSe)_x$, or $(GaAs)_{1-x}(Ge2)_x$

Consider the conditions for the formation of SS substitution based on elements of group IV. For such systems, conditions (3) and (4) have the following form:

where z_A, z_B and z_C are the valencies, r_A, r_B and r_C are the covalent radii of the elements of group IV, respectively. The table shows the values of the sum of the covalent radii of atoms of molecules of group IV elements. Values of the sum of the covalent radii of atoms of molecules of group IV elements.

A_2^{IV}, $A^{IV}B^{IV}$	C_2	Si_2	Ge_2	Sn_2	SiC	GeC	SnC	SiGe	SiSn	GeSn
$r_{IV}+r_{IV}$, Å	1.54	2.34	2.44	2.80	1.94	1.99	2.17	2.39	2.57	2.62

Based on the data in the table and conditions (5) and (6), we selected 8 possible cases of the formation of SS substitutions: $Si_{1-x}Ge_x$, $(Si_2)_{1-x}(SnC)_x$, $(Si_2)_{1-x}(SiSn)_x$

$(Sn_2)_{1-x}(SiSn)_x$, $(Ge_2)_{1-x}(GeSn)_x$ $(Sn_2)_{1-x}(GeSn)_x$, $(Ge2)_{1-x}(SiSn)_x$ $(GeSi)_{1-x}$ $(SiSn)_x$, $(GeSn)_{1-x}(SiSn)_x$, $(GeSi)_{1-x}(GeSn)_x$, $(SiC)_{1-x}(GeC)_x$, $(GeC)_{1-x}(SnC)_x$, $(SnC)_{1-x}(SiGe)_x$. It should be noted that Ge and Ni can form SS substitutions in two different variants due to the substitution of Ge_2 and GeSn or Sn_2 and GeSn molecules (Fig. 1), while the difference in the sum of the covalent radii of the atoms of Ge_2, GeSn, and Sn_2 molecules is ~ 7%. Since 2r Ge <r Ge + r Sn, therefore,the Ge – Sn molecular bond in the Ge environment (Fig. 1a) will exist, and in the Sn environment, due to the relation 2r Sn> r Ge + r Sn, it will stretch.Such elastic deformations and hybridizations of GeSn electron shells with surrounding atoms lead to the appearance of a kind of energy spectrum of $Si_{1-x}Ge_x$ – Ni covalent bonds in the tetrahedral solid solution lattice. Under the influence of surrounding, more strongly bound Ge – Ge, one should expect an increase in the binding energy of atoms of $Si_{1-x}Ge_x$ – Ni molecules, and under the influence of more weakly knitted Ni – Ni, its decrease.

In the case of elements of Ge, Si, and Ni, there are 4 possible varieties of the formation of SS substitution: $(Ge_2)_{1-x}$ $(SiNi)_x$, $(GeSi)_{1-x}$ $(SiNi)_x$, $(GeNi)_{1-x}$ $(SiNi)_x$, $(GeSi)_{1-x}$ $(GeNi)_x$. The behavior of SiNi and GeNi molecules in the tetrahedral lattice of a solid solution will be different depending on the atoms surrounding it. It should be noted that the possibility of the formation of SS substitution of C_2 with Si_2, Ge_2, Ni_2, SiC, GeC, NiC, SiGe, SiNi, GeNi; Si_2 with SiC, GeC, GeNi; Ge_2 with SiC, GeC, NiC; Ni_2 with SiC, GeC, NiC, SiGe is negligible.

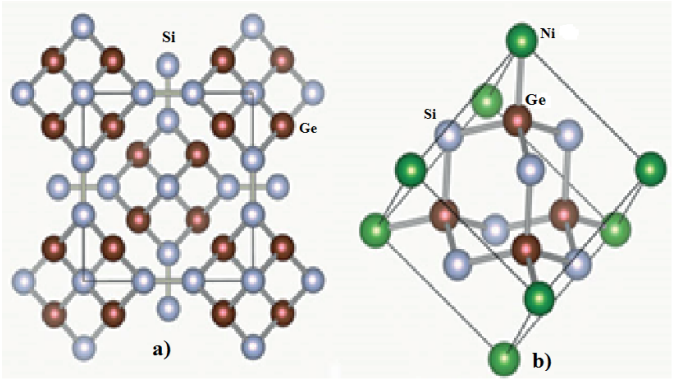

Fig. 1. Spatial configurations of two tetrahedral bonds of a substitutional solid solution $Si_{1-x}Ge_x$-a), $Si_{1-x}Ge_x$ – Ni-b)

Note that the Ge – Sn system is also among the promising pairs that form solid solution substitutions. In [4] some preliminary results of our work on obtaining solid solution Fig. 1. substitution Ni_y $(Si_{1-x}Ge_x)_{1-y}$.

2.2 Nickel germanosilicides obtained on the surface of bulk $Si_{1-x}Ge_x$ crystals

The film layers of nickel germanosilicides are attractive in that they are compatible with silicon planar technology, and they play an important role in obtaining ohmic contacts in the manufacture of modern microchips and integrated circuits. On the other hand, it is possible to synthesize them at relatively low temperatures in comparison with other silicide, and high processing temperatures are not required.

This work is devoted to studies of some properties of nickel germanosilicides films obtained by burning a nickel film deposited on bulk single crystals of $Si_{1-x}Ge_x$ solid solutions.

$Si_{1-x}Ge_x$ single crystals were grown by electronless beamless zone melting in a vacuum of 10^{-5}-10^{-7} Torr, which had p-type conductivity with a constant composition (the germanium content remains constant along the crystal). For the preparation of experimental samples, $Si_{1-x}Ge_x$ single crystals were cut into washers 600 μm thick in the <111> direction perpendicular to the growth axis. The resistivity of these plates varied in the range of 100 - 500 Ωsm.

After mechanical and chemical treatments, a thin layer (~ 100 nm) of nickel (99.999%) was applied to the surface of the plates by thermal spraying in vacuum (with a residual pressure of 10^{-6}-10^{-7} Torr). Then, the samples were also annealed in vacuum (10^{-6}–10^{-7} Torr) at temperatures of 200, 300, 400, 500, 600, 700, 800, and 900°C for 10 hours.

The surface morphology and chips of the samples were studied using MII-4 and MIM-8 microscopes. A photograph of the surface taken with a digital camera of one of the samples after annealing at 600 ° C is shown in Fig. 2.
To study the phase state of the nickel germanosilicide films, the X-ray diffraction method was used. Fig. 3. The spectrum of reflections from the sample obtained as a result of the solid-phase reaction of nickel and $Si_{1-x}Ge_x$ after annealing at a temperature of 600°C is presented.

3. Structural and photoelectric parameter measurements heterostructures p / $Si_{1-x}Ge_x$ - n / Ni_y $(Si_{1-x}Ge_x)_{1-y}$ ($0 \le x \le 0.07$)

3.1 Structural studies of $Si_{1-x}Ge_x$ solid solution

Structural studies of the Si1-xGex x solid solutions ($0 \le x \le 0.07$) were performed on a Dron-UM1 X-ray diffract meter (CuKα radiation, $\lambda = 0.15418$ nm) according to the $\theta - 2\theta$ scheme in the stepwise scanning mode. For this purpose, specially grown samples having thin layers (3–5 μm) were chosen. The exposure time varied in the range of 1–3 h. In Fig. 3 presents the x-ray diffraction pattern. It can be seen that in the diffraction pattern at a non-monotonous level of

the background, there are two structural reflections of a selective nature with different intensity.

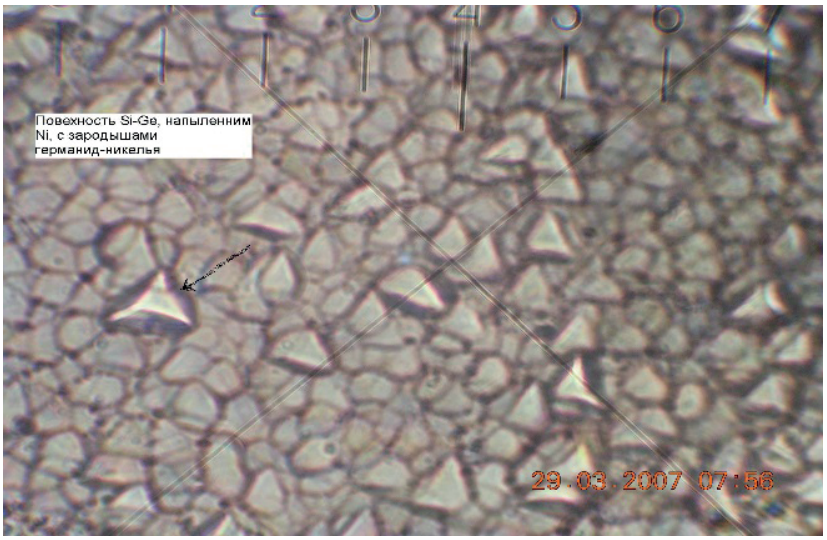

Figure 2. The surface of the Ni / $Si_{1-x}Ge_x$ structure annealed at a temperature of 600°C.

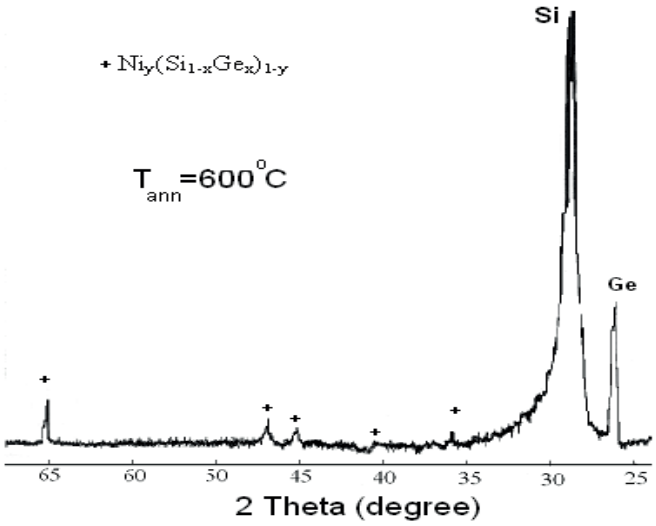

Fig.3. X-ray reflection spectrum from a Ni film ($Si_{0.93}Ge_{0.07}$), formed on a $Si_{0.93}Ge_{0.07}$ substrate at an annealing temperature of 600°C. + - reflection peaks corresponding to nickel germanosilicide.

The detected peaks of germanosilicides in the series of peaks of silicon and germanium show the presence in the <111> direction in the composition of the film. As is known from the literature, nickel germanides are first formed at low temperatures, and nickel germanosilicides and silicides begin at higher temperatures [10]. It can be seen from Fig. 3 that the intensive formation of silicides and the formation of a film of nickel germanosilicide with a high Si content lead to the formation of a spectrum similar to that of silicides.

3.2 Surface resistance of $Ni_y(Si_{1-x}Ge_{x1-y}$ films and current-voltage characteristics of p / $Si_{1-x}Ge_x$ - n / Ni_y ($Si_{1-x}Ge_x)_{1-y}$ structures obtained on bulk $Si_{1-x}Ge_x$ crystals

As shown by numerous studies, to obtain uniform Ni_y $(Si_{1-x}Ge_x)_{1-y}$ films, nickel films on $Si_{1-x}Ge_x$ solid solutions must be larger than 15 nm before annealing []. This section presents the results of studies of the dependence of the surface resistance of Ni_y $(Si_{1-x}Ge_x)_{1-y}$ films and the I – V characteristics of p / $Si_{1-x}Ge_x$ - n / Ni_y $(Si_{1-x}Ge_x)_{1-y}$ structures obtained at different temperatures. Single crystals of $Si_{1-x}Ge_x$ solid solutions were grown by electron beamless crucible zone melting and cut into washers 600 μm thick in the <111> direction, whose resistivity ranged from 100 to 500 Ωsm.

After mechanical and chemical treatments, a thin layer

(~ 100 nm) of nickel (99.999%) was applied to the surface of the plates by thermal spraying in vacuum with a residual pressure of 10^{-6}-10^{-7} Torr and annealing was performed at temperatures of 200, 300, 400, 500, 600 , 700, 800 and 900°C within 10 hours.

The dependence of the surface resistance of Ni_y $(Si_{1-x}Ge_x)_{1-y}$ films (Fig. 4) on the annealing temperature was studied. Surface resistance was measured by the four-probe method [10] at room temperature. As can be seen from Fig. 4, the surface resistance of the samples varies depending on the temperature of the formation and modification of Ni_y $(Si_{1-x}Ge_x)_{1-y}$, as well as on their composition. For example, in the temperature range 200 - 600°C, with an increase in the annealing temperature, the surface resistance of the Ni_y $(Si_{0.93}Ge_{0.07})_{1-y}$ film decreases to 2.0 Ω / sm^2. Further, in the temperature range 600-900 ° C, (R_{sheet}) increases sharply, i.e. After annealing at temperatures T_{ann}> 650 ° C, intensive silicide formation begins. This can be explained as follows: apparently, the (R_{sheet}) of the Ni_y $(Si_{0.93}Ge_{0.07})_{1-y}$ film depends on the formed chemical phase and film morphology, as well as on strong agglomeration and formation of nickel silicide islands[13].

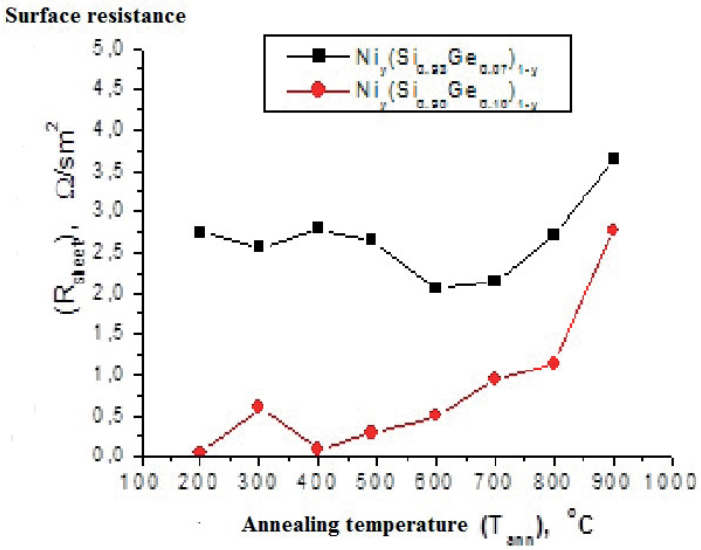

Fig.4. Dependence of surface resistance on the temperature of formation of nickel germanosilicide films.

According to estimates, the thickness of the Ni_y($Si_{0.93}Ge_{0.07})_{1-y}$ layer is ~ 0.02 μm [10]. To confirm this assumption, the upper layers enriched with nickel were removed to the film by selective etching of the samples in a CP-4 solution, and the type of conductivity was determined. Moreover, some plates had n-type conductivity. The reason for this may be nickel atoms, since nickel is an amphoteric impurity in silicon, and they will create two levels (acceptor - 0.35 eV and donor (acceptor) - 0.23 eV). The influence of these levels on the type of conductivity of the films has not yet been clarified, which requires further research in this direction.

Also, at room temperature, the I – V characteristics of p / $Si_{1-x}Ge_x$ - n / Ni_y $(Si_{1-x}Ge_x)_{1-y}$ structures obtained on the basis of Ni_y $(Si_{1-x}Ge_x)_{1-y}$ films annealed at different temperatures were measured (Fig. 4). As can be seen from Fig. 5, the I – V characteristics is characterized by a high coefficient of rectification.

With an increase in the annealing temperature, the formation of silicides begins, a change in the modification of germanides and silicides, which leads to an increase in the reverse current and a decrease in the breakdown voltage. With a further increase in the annealing temperature (above 650 ° C), intense formation of nickel silicide begins, accompanied by annealing of defects. As a result, the reverse currents begin to decrease and the breakdown voltage increases.

Thus, it has been shown that a structural change in nickel silicide occurs in the temperature range 200-900°C, and their intensive formation begins at a temperature T_{ann}> 650°C. It should be noted that the surface resistance of the Ni_y $(Si_{1-x}Ge_x)_{1-y}$ film on the studied samples varies 3-5 times, and the I – V characteristic p / $Si_{1-x}Ge_x$ is n / Ni_y $(Si_{1-x}Ge_x)_{1-y}$ structures and the surface resistance correlates with a change in structure during annealing.

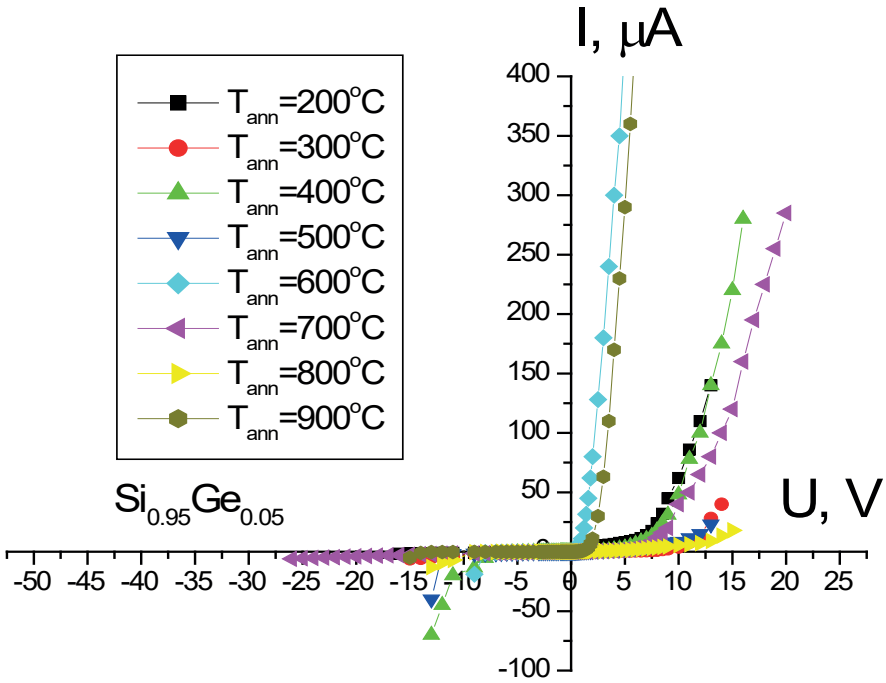

Fig.5. The family of I – V characteristics p / Si1-xGex - n / Niy (Si1-xGex) 1-y structures obtained on the basis of nickel germanosilicides annealed at various temperatures.

The results of this project can be used in the manufacture of ohmic contacts for nuclear radiation detectors, solar cells, and devices with a Schottky barrier based on bulk $Si_{1-x}Ge_x$ crystals.

3.3 Spectral photosensitivity of heterostructuresnickel germanosilicide ($0 \le x \le 0.07$)

Using annealing in a vacuum medium with deposition on a $Si_{1-x}Ge_x$ surface,

p / $Si_{1-x}Ge_x$ - n / Ni_y $(Si_{1-x}Ge_x)_{1-y}$ x ($0 \le x \le 0.07$) heterojunctions with a transitional graded-gap buffer layer consisting of SS substitution of nickel. The composition of the transition layer varies in film thickness; closer to the substrate, $Si_{1-x}Ge_x$ prevails, and as the layer grows, the molar content of Ni increases. To elucidate the role of SS components, we experimentally investigated the spectral dependence of the photosensitivity of fabricated structures using an IKS-21 infrared spectrometer. The measurement results are presented in Fig. 6. From fig.6 shows that the photosensitivity of the studied structures covers the photon energy range from 0.9 to 2.5 eV. The photosensitivity edge of Ge p – n junctions is known to be 1.07 eV. The shift of the sensitivity of the studied structures to the longer wavelength side is due to the SS p / $Si_{0.97}Ge_{0.07}$ - n / $Ni_{0.03}$ $(Si_{0.93}Ge_{0.07})_{0.97}$.

However, the increase in spectral sensitivity is not sharp, which is possibly due to the thickness of the SS layer p / $Si_{0.93}Ge_{0.07}$ - n / $Ni_{0.03}$ $(Si_{0.97}Ge_{0.07})_{0.97}$, which effectively absorbs low-energy quanta. Since p/$Si_{0.93}Ge_{0.07}$-n/$Ni_{0.03}$(-$Si_{0.93}Ge_{0.07})_{0.97}$ is an indirect gap semiconductor, a layer of sufficient thickness, apparently more than 15 μm, is required to complete the absorption of long-wavelength photons. The decrease in photosensitivity at photon energies greater than 1.35 eV is due to the depth of the p – n junction separation barrier, which in our case is determined by the thickness of the epitaxial layer and amounts to ~ 15 μm. The diffusion length of minority carriers in the p / $Si_{1-x}Ge_x$ - n / Ni_y $(Si_{1-x}Ge_x)_{1-y}$ layer, as shown above, is ~ 1.6 μm, which is less than the depth of the separation barrier. Therefore, electron – hole pairs generated in the surface region of the structure by short-wavelength photons do not reach the separating barrier and do not participate in the creation of a photocurrent, which is the main reason for the decrease in the photo sensitivity of the studied structure in the short-wavelength region of the radiation spectrum.

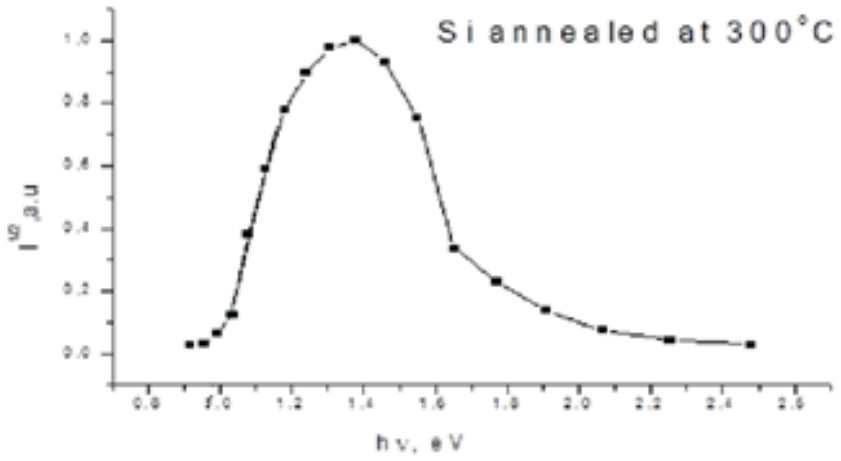

Fig. 6. Spectral photosensitivity of heterostructures p/$Si_{1-x}Ge_{x-n}$/$Ni_y(Si_{1-x}Ge_x)_{1-y}$ ($0 \le x \le 0.07$) at room temperature.

4. Conclusion

1. Analyzing the results of the studies and evaluating the prospects of using single crystals of the $Si_{1-x}Ge_x$ alloy, we can say the following: large-scale instrumentation using the $Si_{1-x}Ge_x$ alloy is possible when using crystals grown by the Chohralski method. Since one of the requirements of modern semiconductor production is the large diameter of the washers (> 2.5 inches), which requires a significant improvement in the quality of the crystals, uniform distribution of their properties.

$Si_{1-x}Ge_x$ single crystals grown by electron beam zone melting have the prospect only for basic and applied research, as well as for the development of special devices that do not require large crystals.

2. Based on the research results, it can be concluded that the peaks found in the reflection spectrum show the presence of germanosilicides in the film. Consequently, nickel germanosilicide films were obtained on bulk single crystals of $Si_{1-x}Ge_x$ solid solutions and it was shown that nickel germanides are formed at low temperatures, and nickel germanosilicides and silicides begin to form at higher temperatures. The research results showed that in the temperature range 200-900°C, a structural change in nickel silicide occurs, and their intensive formation begins with a temperature T_{ann} > 650°C.

3. It should be noted that the surface resistance of the $Ni_y(Si_{1-x}Ge_x)_{1-y}$ film on all samples studied varies by a factor of 3-5. The I – V characteristics p / $Si_{1-x}Ge_x$ - n / Ni_y ($Si_{1-x}Ge_x$) of the 1st structure and surface resistance correlate with a change in the structure during annealing.

4. The results of this work can be used in the manufacture of ohmic contacts for nuclear radiation detectors, solar cells, and devices with a Shottky barrier based on bulk crystals, $Si_{1-x}Ge_x$.

5. Thus, it has been shown that it is possible in principle to grow perfect single-crystal films of a $Si_{1-x}Ge_x$ substitutional solid solution with the (111) crystallographic orientation on single-crystal Ge substrates by liquid-phase epitaxy from a tin-molten solution. The mismatch between the constant lattices of the $Si_{1-x}Ge_x$ solid solution film ($0 \le x \le 0.07$) (a_f = 5.4451323 $\dot{A}$) and the $Si_{1-x}Ge_x$ substrate (a_s = 5.6561 $\dot{A}$) was

$$\xi = \frac{2|a_s - a_f|}{a_s + a_f} = 0.038$$

The photosensitivity of n / Ni_y ($Si_{1-x}Ge_x$) 1-y heterostructures ($0 \le x \le 0.07$) covers the spectral range of photon energy from 0.9 to 2.5 eV. The grown thin epitaxial layers can be used as a photoactive material for the design of optoelectronic devices operating in the infrared region of the radiation spectrum, or as a substrate material for further growth of solid solutions on them with lattice parameters close to 5.4451323 $\dot{A}$.

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